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COMPUTATION AND APPLICATION OF THE TOPEX/POSEIDON ORBIT EVENT FILE

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The Orbit Event Program is an analytical software tool that searches for the occurrence of various satellite geometries relative to the earth, sun, Deep Space Network stations, and the Tracking and Data Relay Satellite System. The Orbit Event Program is used by the TOPEX/POSEIDON Navigation Team to generate an Orbit Event File, which consists of a select group of time-ordered events to be used in mission planning for the TOPEX/POSEIDON spacecraft.

Prior to launch, the Orbit Event Program was used extensively in the design of the TOPEX/POSEIDON operational orbit and the assessment phase maneuver sequence. During routine operations, the Orbit Event File is delivered to the Mission Planning and Sequencing Team on a weekly basis. From the Orbit Event File, the mission planners generate a Sequence of Events to be uplinked to the satellite. The Orbit Event File is also used as input to the TDRSS scheduling process.

This paper provides an overview of the Planetary Observer Planning Software, from which the Orbit Event Program has evolved as an application specifically for the TOPEX/POSEIDON mission. The various orbital events computed and written to the Orbit Event File are described, and the application of the Orbit Event File in mission planning is discussed. The accuracy of the events calculated by the Orbit Event Program, as compared with the actual observed orbital events, are evaluated.

INTRODUCTION

TOPEX/POSEIDON is a cooperative project between the United States and France to develop and operate an advanced satellite system dedicated to observing the Earth's oceans. The mission is providing global sea level measurements with an unprecedented accuracy, using radar altimetry. The data from TOPEX/POSEIDON will be used to determine global ocean circulation and to understand how the oceans interact with the atmosphere.

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During the TOPEX/POSEIDON mission design process, the need was identified for software capable of generating a predicted set of orbital events for use in view period scheduling and sequence planning. As a result, the Mission Design Section of the Jet Propulsion Laboratory developed the Orbit Event Program as an extension of the Planetary Observer Planning Software. The Orbit Event Program is an analytical software tool that searches for the occurrence of various satellite geometries relative to the earth, sun, Deep Space Network (DSN) stations, and the Tracking and Data Relay Satellite System (TDRSS). In general, the events computed by the Orbit Event Program are functions of the spacecraft trajectory and attitude.

The Orbit Event Program is used by the TOPEX/POSEIDON Navigation Team to generate an Orbit Event File, which consists of a select group of time-ordered events to be used in mission planning for the TOPEX/POSEIDON spacecraft. These events include orbit revolution occurrences, land/sea crossings, verification site closest approaches, DSN station rises and sets, TDRSS rises and sets, spacecraft occultations from the sun, solar interference with communication links, orbit sun times, beta-prime events, and Radio Frequency Interference (RFI) and South Atlantic Anomaly zone entries and exits. Events related to the TOPEX/POSEIDON High Gain Antenna orientation and gimbal angle rates are also included.

During mission operations, the GSFC Flight Dynamics Facility provides the Jet Propulsion Laboratory TOPEX/POSEIDON Navigation Team with orbit determination solutions based on tracking data, in the form of Extended Precision Vectors (EPVs). The EPVs are transmitted via NASCOM through the Telemetry, Command and Communications Subsystem from the Flight Dynamics Facility to the TOPEX/POSEIDON Navigation Team. The Navigation Team converts the vectors into mean elements for use in orbit propagation. The Satellite Performance Analysis Team provides constraints related to the satellite geometry for input into the Orbit Event Program. The resulting Orbit Event File is then delivered by the Navigation Team to the Mission Planning and Sequencing Team for use in developing the mission sequence.

Prior to launch, the Orbit Event Program was used extensively in the design of the TOPEX/POSEIDON operational orbit and the development of the assessment phase maneuver sequence. During routine TOPEX/POSEIDON operations, the Orbit Event File is delivered to the Mission Planning and Sequencing Team on a weekly basis. From the Orbit Event File, the Mission Planners generate several products. The events of the OEF are incorporated into the Sequence of Events and the Space Flight Operations Schedule. The Sequence of Events is a listing of the stored and real-time commands to be uplinked to the satellite, while the Space Flight Operations Schedule is a timeline of TOPEX/POSEIDON activities in graphical form. The Orbit Event File is also used as input for the TDRSS Resource User's Scheduling Tool software, developed by the University of Colorado for scheduling TDRSS and DSN activities. The Mission Planning and Sequencing Team also uses the land/sea crossing information provided in the Orbit Event File to determine appropriate times to enact special procedures, such as altimeter boresight calibration maneuvers.

A thirty-second accuracy requirement was placed on the Orbit Event Program by the TOPEX/POSEIDON Ground System. More specifically, it is required that each event time printed to the Orbit Event File be accurate to within thirty seconds of the actual orbital event experienced by the spacecraft. A variety of methods have been employed to test individual print events in the OEP, including a rigorous comparison with a Predicted Site Acquisition Table (PSAT) supplied by NASA Goddard Space Flight Center. Ongoing experience has motivated refinements in the models employed by the Orbit Event Program, to increase accuracy in the computation of orbital events. Flight data received in the telemetry during TOPEX/POSEIDON operations has verified the accuracy of the events written to the Orbit Event File.

PLANETARY OBSERVER PLANNING SOFTWARE OVERVIEW

The Planetary Observer Planning Software (POPS) is a high speed, medium accuracy mission design tool for the analysis of planetary orbits[1]. The POPS software set consists of two state propagators (one models short term orbital motion, while the other averages out short term behavior in order to provide greater computational speed[2]), an ephemeris post processor, and a graphics software package.

The Planetary Observer Long Term Orbit Predictor (POLOP) propagates an initial set of mean orbital elements to a future epoch, using mean-averaged orbital elements for computational speed. POLOP is used for long term propagations when modeling the short period motion is not required. Forces modeled by POLOP include gravity spherical harmonics, atmospheric drag, solar radiation pressure, and luni-solar third body effects. POLOP creates an ephemeris file for use by the post-processor software.

The Planetary Observer High Precision Orbit Propagator (POHOP) is used when short term orbital behavior must be modeled. POHOP propagates osculating orbital elements from an initial epoch to a future epoch, using force models similar to those employed by POLOP. POHOP has the added capability of modelling mass concentrations in the central body. The computational algorithms used by POHOP are of higher accuracy than those for POLOP, although the computational speed is greatly reduced for POHOP..

The only external file required to run POLOP or POHOP is a gravity field file which contains the unnormalized spherical harmonic coefficients used in modeling the planet's gravity field. The Goddard Earth Model T2 is currently used by TOPEX/POSEIDON mission operations for the generation of POPS ephemeris.

The Planetary Observer Post Processor (POPP) utilizes the spacecraft ephemeris, created by POHOP or POLOP, to search for various trajectory- or attitude-related geometries. At occurrences of these events, POPP outputs a variety of user-specified data. POPP may also use an internal, low precision spacecraft ephemeris instead of the more accurate ephemeris files generated by POHOP or POLOP. The low precision spacecraft ephemeris is generated by propagating the initial spacecraft state forward in time to a future epoch, using the J2 secular equations.

The Orbit Event Program (OEP) has evolved as a TOPEX/POSEIDON-specific version of POPP. The TOPEX/POSEIDON yaw steering control algorithm for solar pointing has been implemented as an option to the OEP. Solar panel blockage of the TOPEX/POSEIDON high gain antenna is modeled, and inputs are read to establish high gain antenna gimbal angle and rate constraints. The OEP is maintained in parallel with POPP; refinements and modifications are made to both programs when appropriate. Operational versions of the OEP currently exist on the TOPEX Ground System VAX machine, and in the Mission Design Section at the Jet Propulsion Laboratory on a UNIX-based Sun SparcStation. Minimal modifications are necessary to transfer the software between the UNIX machine and the VAX.

The Planetary Observer Plotting Program (POPLOT) is a graphics package for plotting the data generated by POPP or OEP. POPLOT is often used to plot orbiter groundtracks on a world map with a variety of labeling options, including time tics, rev numbers, and station view zones. POPLOT can also produce view period summaries, nodal crossing summaries, occultation duration plots, and generic X versus Y plots for any orbital data computed by the post processor.

TOPEX/POSEIDON ORBIT EVENTS

The OEP is used by the TOPEX/POSEIDON Navigation Team to generate an Orbit Event File (OEF), which consists of a select group of time-ordered events to be used in mission planning for the TOPEX/POSEIDON spacecraft. For each event, the day number and time of the event, cycle number, pass number, rev number, latitude, longitude, event mnemonic, and event identification number are written to the OEF. In addition to the OEF, a variety of orbital parameters can be written to an ASCII file upon the occurrence of specific orbit events, or at user-defined time steps.

This section contains a description of the orbit events that are computed by the OEP and written to the OEF.

Orbit Revolution Events

This event category includes ascending node crossings, ascending and descending pass events, and orbit cycle events[3]. The ascending node event is triggered at each spacecraft ascending equatorial crossing. The ascending pass event is activated when the spacecraft reaches minimum latitude in its orbit, and the descending pass begins when the spacecraft reaches its maximum latitude. The orbit cycle event is triggered at the completion of each groundtrack repeat cycle. The orbit cycle is defined to begin at the start of an ascending pass. For TOPEX/POSEIDON, the orbit groundtrack repeat cycle is 127 revolutions in approximately 10 days.

Land/Sea Crossing Events

Land/sea events are determined by the spacecraft nadir point crossing an Earth land/sea boundary. The current land map data in the OEP produces approximately 1° resolution. An effort is currently being made to improve this resolution to 0.2° through the introduction of a digital world map supplied by JPL's Image Processing Facility.

Verification Site Closest Approach

The verification site closest approach event is activated at the time of closest approach of the spacecraft groundtrack to an earth-fixed verification site. Closest approach occurs when the range rate of the spacecraft nadir point with respect to the ground site is zero. The user may specify a boundary range, outside of which closest approach events cannot occur. TOPEX/POSEIDON uses two verification sites: the NASA verification site at Harvest Platform (34.469° N, 239.319° E), an oil drilling unit off Point Conception, California, and the CNES verification site at Lampione Rock (35.546° N, 12.321° E), near Lampedusa Island in the Mediterranean Sea. For the TOPEX/POSEIDON operational orbit, adjacent groundtracks are spaced 316 km apart at the equator. There are passes in the operational orbit cycle (descending at the NASA site, ascending at the CNES site) that overfly relatively close to the verification sites, despite the fact that they are not the nearest overflights to the site. In order to obtain a single closest approach event for each verification site per TOPEX/POSEIDON orbit cycle, the boundary range for closest approach events is set at 20 km.

Deep Space Network Rise and Set Times

This event category is defined by the rise time and the set time of the spacecraft with respect to three Deep Space Network (DSN) ground stations, limited by horizon masks. For these events, it is assumed that omni-directional antennas onboard the spacecraft provide virtually unlimited viewing toward the earth. Thus, viewing depends only on the horizon constraints at the DSN stations. The horizon masks, which model the terrain and DSN station mechanical constraints, are defined by elevation angle as a function of the azimuth angle. These data are obtained from the DSN, and are hard-coded into the OEP as coefficients of a polynomial. The DSN horizon constraints may also be set as a constant elevation angle for use by all DSN stations, specified by user input.

Tracking and Data Relay Satellite System Rise and Set Times

Two Tracking and Data Relay Satellite System (TDRSS) locations are hard-coded into the OEP internal site data base: TDRS East at 41° W, and TDRS West at 174° W. If a different TDRSS location is desired, the new TDRSS location may be input to the OEP. If the desired TDRSS is in an inclined orbit relative to the earth's equator (as is the TDRSS currently located at 171° W), the user may input the Keplerian orbital elements of the TDRSS into the OEP, and the approximate position of the TDRSS is calculated for the appropriate events.

For the TOPEX/POSEIDON mission, the rise and set times of the TDRSS are limited by the high gain antenna field of view constraints, and the high gain antenna angular rate limits. A spacecraft-centered zenith-oriented cone angle is used to specify the geometric line-of-sight rise and set times of the TDRSS. High gain antenna pointing is dependent on spacecraft attitude, making it necessary to implement the spacecraft yaw steering algorithm into the OEP, in order for the TDRSS rise/set events to be computed accurately.

The high gain antenna field of view is limited principally by mechanical and/or software stops in the antenna gimbal angles. Additionally, the spacecraft solar panel may impinge into the high gain antenna field-of-view. The OEP's implementation of the high gain antenna field-of-view constraints is in the form of a mask in gimbal angle alpha/beta space. Figure 1 shows the high gain antenna field-of-view mask employed in the OEP.

Although a TDRS satellite is in the field-of-view of the high gain antenna, limits imposed on the angular rate of the antenna actuators may prevent tracking. The user of the OEP supplies the maximum alpha and beta gimbal angle rates of the high gain antenna as an input.

Solar Occultation Events

The occultation of the sun by the earth as viewed from the spacecraft defines this event. The OEP treats the sun as a point source. The occultation altitude above the earth reference ellipsoid can be changed by user input so that the effects of atmospheric attenuation may be modeled.

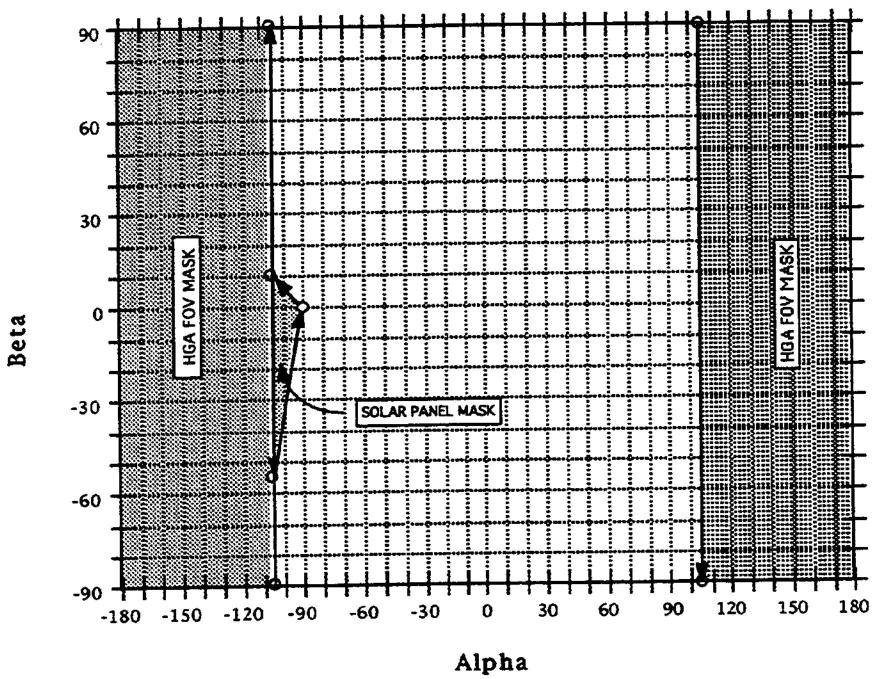

Figure 1. High Gain Antenna Field of View and Solar Panel Mask

Solar Interference with Communications Links

Solar interference occurs for the return link from the spacecraft to the TDRSS satellite, when the spacecraft is near the sun as seen from the TDRSS[4]. A user of the OEP provides a sun interference angle constraint for the spacecraft-TDRSS communications link, which defines the maximum angle between the spacecraft and the sun, as viewed by TDRSS, for which solar interference can occur. For TOPEX/POSEIDON applications, this sun interference angle is 3.5°.

Solar interference can also occur for the communications link between the TDRSS satellites and the White Sands Ground Terminal (WSGT). Solar interference occurs for the downlink from TDRSS to WSGT when the TDRSS satellite is near the sun as seen from WSGT. For TOPEX/POSEIDON applications, solar interference is expected to occur when the TDRSS-sun angle, as viewed by WSGT, is less than 1°.

Orbit Sun Time

There are four orbit sun time events written to the OEF: orbit noon, 6 PM, midnight, and 6 AM. The orbit noon position is that point in the orbit which contains the projection of the earth-sun vector onto the orbit plane, as shown in Figure 2. The orbit 6 AM position occurs when the spacecraft position vector is in the direction of the unit vector defined by the cross product between the earth-sun vector and the orbit angular momentum vector. The orbit midnight and 6 PM orientations occur when the spacecraft position vector is in the direction opposite of the orbit noon and 6 AM positions, respectively.

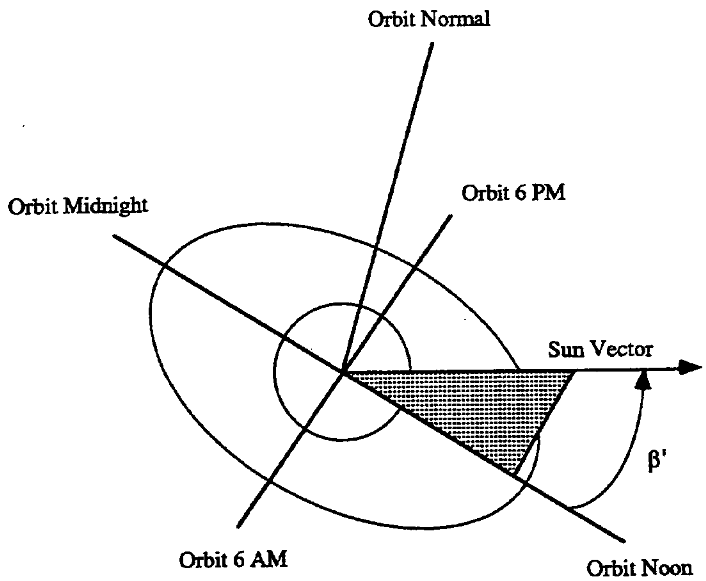

Figure 2. Orbit Sun Time and Beta Prime Angle Definition

Beta-Prime Events

As shown in Figure 2, the beta-prime angle is defined as the angle between the earth-sun vector and the projection of this vector onto the orbit plane, measured positive when the earth-sun vector has a component in the direction of the orbit angular momentum vector. The user of the OEP may specify a set of beta-prime values for which event times are written to the OEF. For the TOPEX/POSEIDON mission, beta-prime events are written when the beta-prime angle passes through 0° and ±15°. The ±15° beta-prime angles are transition regions between fixed yaw and yaw steering of the spacecraft, and a 180° yaw flip maneuver is performed when the beta-prime angle passes through 0°.

Groundtrack Zone Events

This event category is triggered when the spacecraft groundtrack enters or exits a user-defined area, typically a Radio Frequency Interference (RFI) zone or the South Atlantic Anomaly (SAA) zone. The user supplies to the OEP a set of longitude and latitude vertex points that define a polygon. Groundtrack zone polygons used during TOPEX/POSEIDON operations are shown in Figures 3 through Figure 5. Figure 3 is the RFI zone associated with the TDRSS satellite located at 174° W longitude, and Figure 4 shows the RFI zone for the TDRSS at 41° W. The SAA zone used for TOPEX/POSEIDON mission planning is shown in Figure 5.

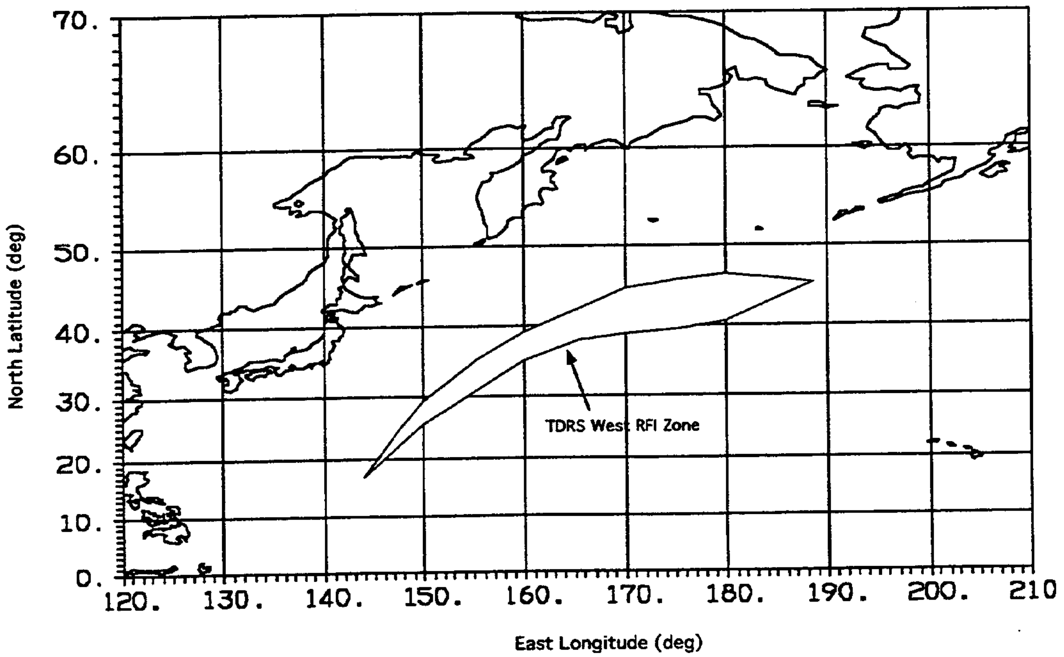

Figure 3. TDRS West RFI Zone

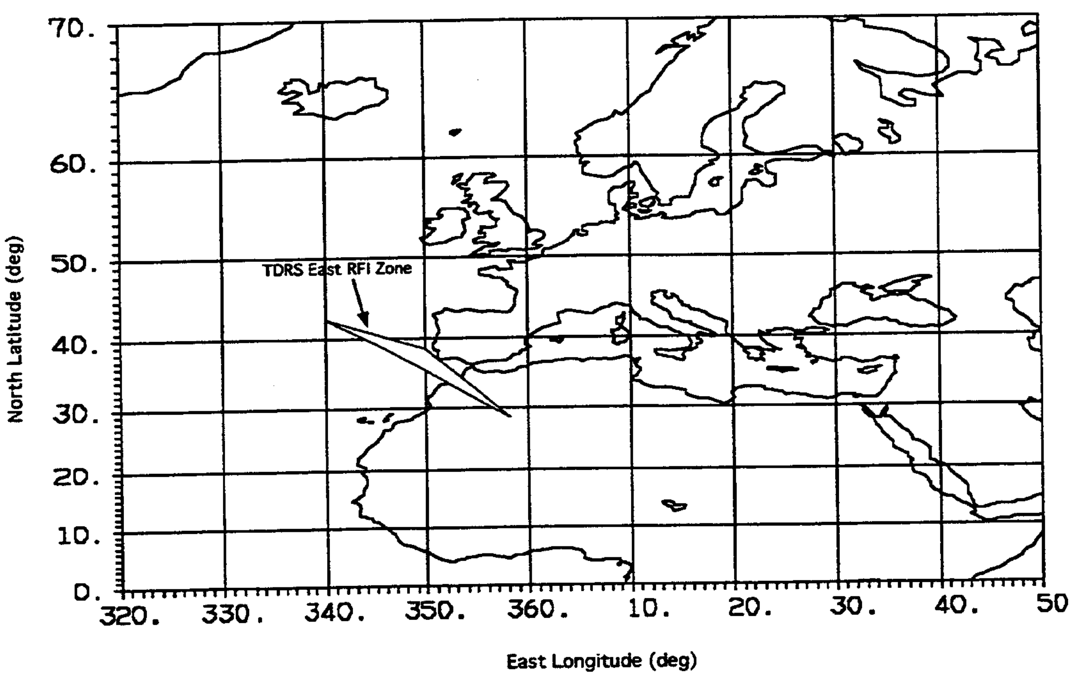

Figure 4. TDRS East RFI Zone

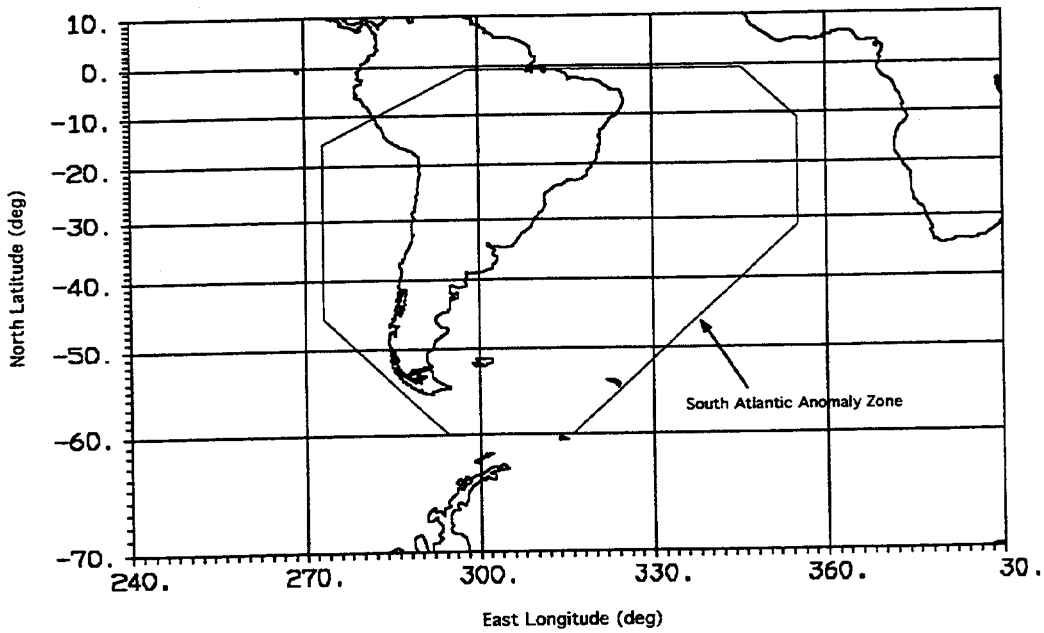

Figure 5. South Atlantic Anomaly Zone

APPLICATION OF THE ORBIT EVENT FILE TO SEQUENCE DEVELOPMENT

The Orbit Event File plays an important role in the development of mission sequences. The event times listed in the Orbit Event File are used by the Mission Planning and Sequencing Team for the development of the Sequence of Events (SOE) and the Space Flight Operations Schedule (SFOS). In addition, an OEF views-chart is also produced by the mission planners, which shows graphically the TDRSS and DSN view periods. The SOE is a listing of the stored and real-time commands and events to be uplinked to the satellite each week, and the SFOS is a timeline of the satellite activities in graphical form. The Orbit Event File is also used by the mission planners for TDRSS scheduling, as input into the University of Colorado's TRUST program. The land/sea crossing data contained in the Orbit Event File are used to schedule appropriate times to enact special procedures, such as altimeter boresight calibration maneuvers. All sequence products are reviewed three times prior to being uploaded to the spacecraft. The sequence is uploaded and run on-board in the fourth week after the OEF delivery.

The Navigation Team has developed a procedure for generating and delivering the Orbit Event File, graphically shown in Figure 6. Reference 6 describes the circumstances for application and use of this procedure in both routine cruise operations and during maneuver planning and execution. An important characteristic of this procedure is the variability of the delivery schedule of the OEF to the Mission Planning and Sequencing Team in different phases of the mission. During routine operations, the OEF is delivered every Thursday, and is generated using the orbital elements received in the latest Extended Precision Vector. The OEF covers the time period four sequences (i.e., four weeks) into the future. During maneuver operations, a preliminary OEF is generated based upon the predicted post-maneuver orbit. If the magnitude of the maneuver is sufficiently large, or if the actual maneuver execution performance deviates sufficiently from the predicted value, an update to the OEF may be required. Each maneuver during the initial assessment phase of the TOPEX/POSEIDON mission required updates to the Orbit Event Files.

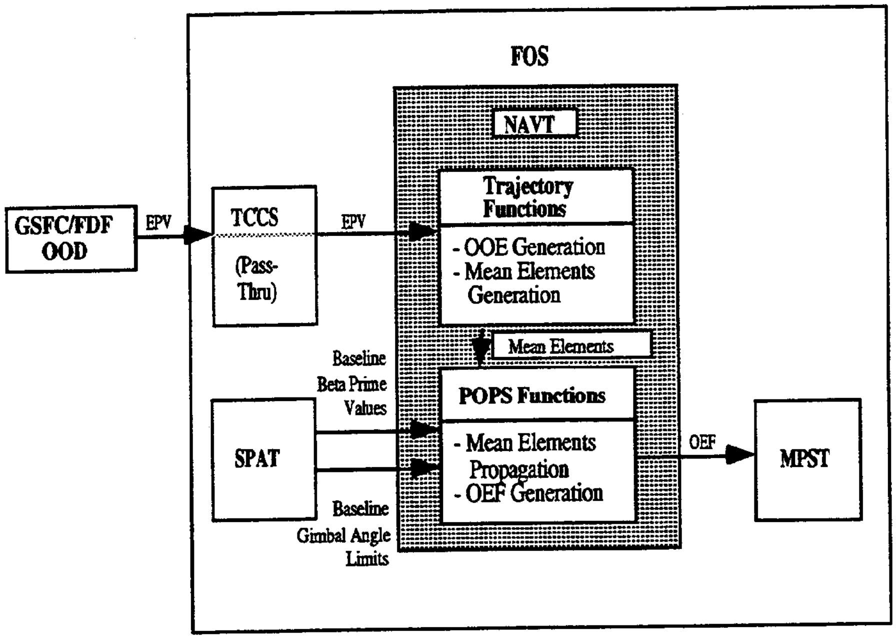

Figure 6. OEF Data Flow Block Diagram

ORBIT EVENT FILE ACCURACY

The TOPEX/POSEIDON Ground System requires the Orbit Event File to predict event times which are accurate to within thirty seconds. Although some events cannot be validated directly, flight data received in the telemetry during TOPEX/POSEIDON operations has verified the accuracy of a number of the events written to the Orbit Event File. Two examples are discussed in this section: solar occultation events and TDRSS acquisition.

Solar occultation events can be monitored directly, using the on-board Coarse Sun Sensor and solar array voltage data. The Orbit Event Program determines solar occultations using a point source sun and an ellipsoid earth with a variable height opaque atmosphere. Initially, the Orbit Event Program used an atmosphere height of 90 km to compute solar occultation duration. When compared with Coarse Sun Sensor data, it was found that the atmosphere model used was overly conservative, resulting in predicted occultation periods longer in duration than the actual events[6]. A more accurate set of occultation predictions was produced by reducing the Orbit Event Program atmosphere height to 27 km. As seen in Table 1, the resulting predictions model the actual events more closely, while still remaining sufficiently conservative to insure that no unpredicted occultations will occur.

The NASA Goddard PSAT provided an excellent source of comparison for TDRSS geometric rise/set events[7]. TDRSS orbital ephemeris data is computed and applied to event predictions in the PSAT, while the Orbit Event Program assumes the TDRSS satellites are located at fixed points above the equator (a more accurate model is available in the Orbit Event Program, which allows the user to specify the Keplerian orbital elements for a single TDRSS satellite in an inclined orbit relative to the equator[8]). The simplified approach used by the Orbit Event Program introduces error into the TDRSS rise/set time computations. Figure 7 shows the difference in TDRS East rise times as computed by the Orbit Event Program, compared with PSAT results. The majority of the rise times predicted by the Orbit Event program differ by less than 30 seconds from the corresponding rise times written to the PSAT.

However, there are periodic differences of over two minutes, and even outlying points with differences of over three minutes. In order to insure that errors due to TDRSS motion do not result in TDRSS view periods being scheduled when the TDRSS satellite is not visible to TOPEX/POSEIDON, the cone angle (measured from the spacecraft nadir) used to determine TDRSS rise/set events is set to 57° for the TOPEX/POSEIDON orbit. The resulting geometric field-of-view of the spacecraft is conservative, producing TDRSS rise times somewhat later than they actually occur, and predicted TDRSS set times that are earlier than the actual events.

Table 1. Coarse Sun Sensor Flight Data Compared with OEP Occultation Predictions

CSS Flight Data UTC Start-Stop Times 1993 DOY hour:min:sec	OEP Predictions (27 km atmosphere height) UTC Start-Stop Times 1993 DOY hour:min:sec	OEP Predictions (90 km atmosphere height) UTC Start-Stop Times 1993 DOY hour:min:sec
013 16:50:36 - 17:24:44	013 16:50:28 - 17:24:45	013 16:50:12 - 17:25:07
013 18:43:06 - 19:17:14	013 18:42:57 - 19:17:12	013 18:42:40 - 19:17:28
013 20:35:36 - 21:09:36	013 20:35:25 - 21:09:39	013 20:35:08 - 21:09:55
013 22:27:58 - 23:02:06	013 22:27:53 - 23:02:06	013 22:27:37 - 23:02:22
014 00:20:29 - 00:54:37	014 00:20:21 - 00:54:33	014 00:20:05 - 00:54:49
014 02:12:59 - 02:46:59	014 02:12:50 - 02:46:59	014 02:12:33 - 02:47:16
014 04:05:29 - 04:39:29	014 04:05:18 - 04:39:26	014 04:05:01 - 04:39:43
014 05:57:51 - 06:31:51	014 05:57:46 - 06:31:53	014 05:57:30 - 06:32:10
014 07:50:21 - 08:24:21	014 07:50:14 - 08:24:20	014 07:49:58 - 08:24:37
014 09:42:51 - 10:16:51	014 09:42:43 - 10:16:47	014 09:42:26 - 10:17:03

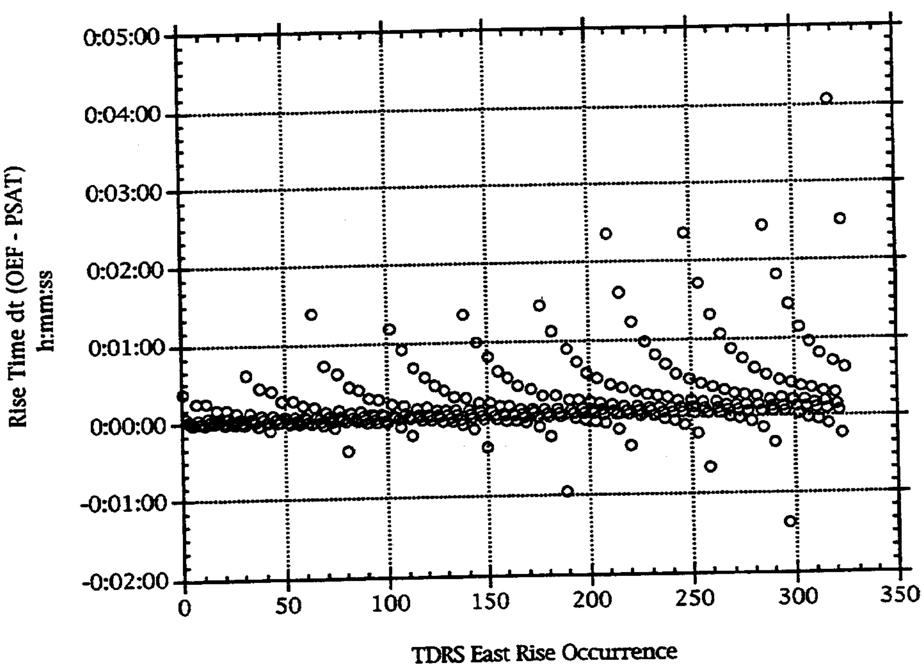

Figure 7. TDRS East Rise Time Comparison, OEF Versus PSAT

CONCLUSIONS

The Orbit Event Program has proven to be a versatile piece of mission operations software with a wide range of applications. It is an integral part of the development of mission sequences, and the general nature of the program has allowed it to be useful in a variety of ad-hoc tasks.

The program may be useful for planetary orbiters other than TOPEX/POSEIDON. Only the events related to the High Gain Antenna field of view are specific to the TOPEX/POSEIDON mission; the remainder of the events may applicable to other missions, including those designed to orbit bodies other than earth.

ACKNOWLEDGEMENTS

The development of the Orbit Event Program has been an evolutionary process, resulting from much dedicated work by a number of people. The authors wish to thank Min-Kun Chung, Dan Johnston, Johnny Kwok, John Smith, and Ted Sweetser for their contributions.

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